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Dynamic spatially explicit mass-balance modeling for targeted watershed phosphorus management
I. Model development

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ABSTRACT

Surface waters are frequently impaired by excessive phosphorus (P) from nonpoint sources, especially in regions of intensive livestock agriculture. Despite concerted efforts to apply new management measures, reductions in nonpoint source P loads have been difficult to accomplish. Watershed management to reduce P export could be more cost-effective if treatments were targeted to critical source areas at high risk for excessive P export. These critical source areas can be defined as the intersection of P source areas and active runoff contributing areas; such areas vary in space and time due to watershed characteristics and management practices. We developed an approach to identify, analyze, and map high-risk areas for P export by integrating spatial data with land use and agronomic data. We evaluated changes over time and space in soil P concentration and P export in response to changes in inputs and outputs with a dynamic mass-balance simulation model running in grid cells across a watershed. The temporal and spatial relationships that define the risk of P export are captured simultaneously using a raster-based distributed dynamic modeling approach and related to management interventions. Simulated responses to management interventions are analyzed and displayed spatially through a geographic information system (GIS). This approach allows the spatial distribution of P runoff risk to be tracked through time in response to long-term P input/output balance, evolving from either continuation of current practices or from management changes specifically targeted to areas of high P loss risk. Baseline simulations show that if present-day management continues, both soil test P and P export will increase dramatically in some parts of a test watershed; critical P source areas in a watershed will evolve over time and are likely to occur in limited areas that can be identified and tracked. Model results can contribute to improved targeting of scarce resources by focusing management interventions on those areas at highest risk of nutrient loss. This paper describes the underlying principles of the model, discusses the process of model development, and presents the final modeling system. Application of the model to alternative management scenarios is discussed in a subsequent paper.

1. Introduction

Many U.S. surface waters are impaired by excessive phosphorus (P) from nonpoint sources (USEPA, 2000). Management to reduce watershed P export is a priority and a challenge, especially in regions of intensive livestock agriculture (Sharpley et al., 1997; Daniel et al., 1994). However, it has proven difficult to integrate specific management actions with the dynamics of human activity, watershed characteristics, and P storage, cycling, and transport processes to achieve P export reduction goals.

Many factors control watershed P export, including hydrology, geology, soils, land use, agricultural and industrial activities, population, and waste treatment (Dillon and Kirchner, 1975; Omernik, 1976, 1977; Clesceri et al., 1986). In agricultural areas, P may accumulate in soils from over-application of nutrients from fertilizer or manure relative to crop need. Excessive soil P levels have been linked to high P losses in runoff, especially in areas of

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animal-based agriculture (Breeuwsma et al., 1995; Pote et al., 1996; Lander et al., 1998; Sims et al., 2000). Contributions to watershed P load from urban land, including wastewater discharges and stormwater, are also significant and may exceed those from agricultural land on an areal basis (Frink, 1991).

Early approaches to nonpoint source P management focused on field-scale transport issues, with erosion control as the principal tool. Subsequently, source issues were also addressed, primarily at the farm scale through nutrient management. More recently, both source and transport issues have been considered at the watershed level (Gburek et al., 2000b). Today, nonpoint source P export from watersheds is understood to be controlled by interaction between P sources and transport mechanisms.

In agricultural watersheds, soils are the major stock of P available for loss, along with fertilizers and manure applied to soils. Soil P content is determined by both management activities (e.g., nutrient application, and cropping) and by soil characteristics (e.g., drainage class, P sorption characteristics). All of these conditions vary spatially. Areas of excessive soil P also vary in time in response to P accumulation or depletion due to changing balance between inputs and outputs.

Transport of P in a watershed occurs mainly through surface runoff and erosion. It is widely believed that only certain watershed areas generate surface runoff that may transport P to a stream. Overland flow results either from infiltration excess, where precipitation cannot infiltrate because rainfall rate exceeds infiltration capacity of the soil, or from saturation excess, where precipitation cannot infiltrate because the soil is already saturated. In the humid Northeast, most storm runoff is believed to derive from saturation excess (Dunne and Black, 1970; Ward, 1984). These saturated runoff contributing areas (RCAs) vary spatially and temporally by geology, topography, soils, rainfall characteristics, and storm magnitude (Dunne and Black, 1970). As RCAs change in size with season or storm magnitude, they are referred to as variable source areas (VSAs) (Dunne and Black, 1970; Frankenberger et al., 1999). In general, only a small proportion of a watershed is believed to be responsible for the majority of P exported in runoff (Sharpley et al., 1994; Daniel et al., 1994; Heathewaite et al., 2000; Walter et al., 2000).

The intersection of high P source areas and probable RCAs defines critical source areas at high risk for excessive P export. Watershed management to reduce P export could be more cost-effective if treatments were targeted to these high P source areas (Gburek et al., 2000a,b). Walter et al. (2001) suggested that a 25% reduction in watershed soluble P loading was possible by adjusting the timing and location of manure application on hydrologically sensitive areas. This kind of management requires the ability to identify source areas, visualize how they may change through time and space, and adjust management programs accordingly. But government programs such as the Environmental Quality Incentives Program (EQIP) (USDA-NRCS, 2005) often ignore the spatial variability of P export risk and strive to promote interventions through voluntary participation across an entire watershed. Without considering hydrologic pathways that govern P transport, blanket management programs are likely to be too restrictive, too expensive, or both.

We developed an approach to identify, analyze, and map high-risk areas for P export by integrating spatial data (e.g., soil characteristics, topography) with land use and agronomic data (e.g., P application rates, cropping patterns). We evaluated changes over time and space in soil P concentration and P export in response to changes in inputs and outputs with a dynamic mass-balance simulation model running in grid cells across a watershed. The temporal and spatial relationships that define the risk of P export are captured simultaneously using a raster-based distributed dynamic modeling approach and related to management interventions. We spatially analyzed and displayed simulated responses to management interventions using a geographic information system (GIS). This approach allows the spatial distribution of P runoff risk to be tracked through time in response to long-term P input/output balance, resulting from either continuation of current practices or from management changes specifically targeted to areas of high P loss risk.

This paper describes the underlying principles of the model, discusses the process of model development, and presents the modeling system. Application of the model to selected management scenarios in a test watershed is presented in Meals et al. (this issue).

2. Modeling approach

We combined principles of watershed mass-balance with the concepts of the P index and variable source area hydrology over a long temporal scale (decades). Our approach included four components – a dynamic watershed mass-balance P model, the Vermont P index, identification of runoff contributing areas, and GIS – combined in a spatial modeling environment.

2.1. Dynamic watershed mass-balance P modeling

Although we ultimately simulate the spatially and temporally dynamic behaviors of P at the watershed scale, the model is based on the building-block of a comprehensive accounting of rates at which P mass enters and leaves a homogeneous land unit (pixel) over time and the amount of P mass stored in that pixel at any time. Dynamic mass-balance models are based on the principle that if the sum of the inputs (fluxes) of P mass into a pixel exceeds the sum of the P mass outputs from the pixel, the mass (stock) of P stored in the pixel increases; if inputs are less than outputs the stock decreases. The amount of P in a pixel is an important determinant of the rate at which P is exported from the pixel. For dissolved P in runoff the rate of export is proportional to soil test P (Sharpley, 1995). This kind of model can be useful for assessing effects of alternative P management scenarios at the pixel-level.

At the watershed level, dynamic P mass-balance modeling can simulate P fluxes and stocks among agricultural, urban, and forest sectors of large watersheds by identifying and quantifying pathways of all significant import, export, cycling, and storage of P within the watershed. These principles are often used to develop scoping models useful in understanding how an ecological system works and to analyze the relative importance of processes and connections (Costanza and Voinov, 2001). This approach has been previously applied to the *Watershed Ecosystem Nutrient Dynamics* (WENDs) modeling process to explore long-term effects of watershed management strategies on environmental and economic goals (Cassell et al., 1998b, 2001, 2002; Aschmann et al., 1999). However, WEND models have not been spatially explicit and typically lump modeled activities into a single mass-balance model for agriculture, forest, and urban sectors, then link sector models together in a watershed model. Our challenge was to make mass-balance accounting for P spatially explicit over a complex watershed.

2.2. The phosphorus index

The P index (Lemunyon and Gilbert, 1993) was developed by scientists from the USDA-Natural Resources Conservation Service (NRCS), USDA-Agricultural Research Service (ARS), and several universities to identify landscape areas where the risk for P accumulation and loss is highest due to P inputs and land